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Energy and environmental benefits in public buildings as a result of retrofit actions

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ABSTRACT

The paper presents the results of an energy and environmental assessment of a set of retrofit actions implemented in the framework of the EU Project "BRITA in PuBs" (Bringing Retrofit Innovation to Application in Public Buildings – no: TREN/04/FP6EN/S07.31038/503135). Outcomes arise from a life cycle approach focused on the following issues: (i) construction materials and components used during retrofits; (ii) main components of conventional and renewable energy systems; (iii) impacts related to the building construction, for the different elements and the whole building.

The results are presented according to the data format of the Environmental Product Declaration.

Synthetic indices, as energy and GWP payback times, and energy return ratio, are defined to better describe the energy and environmental performances of the actions.

The project highlights the role of the life cycle approach for selecting the most effective options during the design and implementation of retrofit actions.

Contents

1. Introduction

A building consumes a significant amount of energy over its life-time [1]. The energy consumption of buildings in the EU is about 40% of the total energy demand [2]. Buildings consume 40% of the materials entering the global economy and generate 40–50% of the total output of greenhouse gases [3]. These figures imply the need for efficient design and quality-oriented construction policies in the EU for sustainability.

Although the literature presents several studies that assess single phases of a building life cycle, there are few papers that analyse the Gross Energy Requirement (GER) and the

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Global Warming Potential (GWP) over the whole life cycle of a building.

Moreover, buildings are long-lasting products that have a significant impact on the environment throughout their lives. Building design should consider long-term environmental benefits [4]. However, traditional environmental assessments generally focus on a few life cycle phases, and analysts typically deal with direct environmental impacts and neglect the external and indirect effects due to suppliers, retailers and consumers activities [5]. Energy and environmental analyses limited to assessing the impacts of the building operation phase are incomplete and misleading, and other life cycle phases (production and manufacture of construction materials, building construction and maintenance, building dismantling and material disposal) should be taken into account [6].

In the EuP (Energy using Products) Directive, the European Commission (EC) introduces the life cycle approach to encourage designers and producers to develop strategies and solutions to reduce the environmental impact of products (eco-design) [7].

This approach should also be applied in the building sector. Several member states have made some initial attempts to integrate environmental criteria in the regulations for the design and construction of buildings [8]. Recently, EU legislative activities have mostly focused on building energy performance and energy certification [9].

Considerable efforts have been made to reduce the energy used for building operation, e.g., improved insulation, reduced air leakage through the building envelope and heat recovery from ventilation air [10]. Such measures result in lower space heating demand, but increase material use, and thus increase the production energy demand. Therefore, the embodied energy of building materials and energy plants increases, and the energy use in the operation phase is comparable to those of other phases [11]. Some studies show that 40–60% of the life cycle energy is used in the production and construction phases [12]. Therefore, the role of the life cycle energy performance should be highlighted and strengthened in future European building legislation.

Moreover, the above considerations should be applied to building refurbishment. Designing an effective building retrofit requires an exhaustive study of all solutions involving planimetric and volumetric changes and exclusion of the obsolete building elements [13]. Housing renovation should reduce the environmental impact (e.g., energy and resource consumption, emission of air and water pollutants, waste generation, and noise), increase the indoor comfort, and improve the architectural appearance of the building facades.

2. Global environmental impact of buildings

Many studies have shown that the operation phase accounts for the majority of the energy consumption in the building life-time. Some of the life cycle analyses carried out on low-energy houses focus on minimising the final energy use or the purchased energy in the operation phase, while the energy consumption in other phases is often neglected [14–16].

An interesting Swiss study was performed to assess the energy consumption of the construction sector [17]. It was estimated that buildings are responsible for the consumption of about 50% of the primary energy in Switzerland. This consumption was mainly related to indoor air-conditioning and sanitary hot water (50–70% of the total consumption) and the production of building materials (10–20%) [18].

Another analysis compared six semi-detached houses in central Europe, with surface areas that range from 176 m^2 to 185 m^2 and an average life-time of 80 years [19]. The houses had heating systems with different energy efficiencies and different building materials. The energy standard of the reference house met the legal requirements set in Germany (in effect since 1995) and corresponded to the mandatory energy standard for buildings in Germany. The reference house had a heating energy demand of 353 MJ/(m^2 year). The other houses had energy consumption values between 122 and 187 MJ/(m^2 year), which are characteristic of low energy houses. The houses only differed slightly in their sizes and layouts. The study showed that adopting high-efficiency design solutions, such as higher insulation, high-efficiency equipment, and low energy materials, lowers the total energy demand with respect to a common reference building.

A life cycle assessment case study was conducted for a 7300 m^2, six-story building with a projected 75-year life-time at the University of Michigan [20]. Operation phase activities consisted of heating, cooling and ventilating the building, lighting and equipment operation, water supply, water heating, and wastewater treatment. The results showed that the energy consumption and environmental impact were concentrated in the operational phase of a building. In fact, production and transportation of building materials and the construction of the building accounted for 2.2% of the primary energy consumption over the life-time of the building. The building operational energy demands over a 75-year life time represented 97.6% of the total primary energy consumption for HVAC, lighting, appliances, and general services (94.4%), and water services (3.2%). Building demolition and transportation of waste accounted for only 0.2% of the primary energy consumption over the life-time of the building.

The details of how the life cycle impacts building components were presented in an analysis of a low energy residential building in Sweden [1]. Energy for material production, building installation and maintenance and replacement was assessed. The yearly energy demand for operation (heating, hot water, household electricity and electricity for fans and pumps) was estimated to be 162 MJ/m^2 year. Assuming a life-time of 50 years, the embodied energy accounted for 40% of the total primary energy requirement.

A recent study presented an environmental assessment of a single-family Italian house. The analysis was performed by collecting and estimating data from each phase of the building, including the design phase, production of construction materials and components, energy and water supply, construction and installation of plants, use, maintenance and management of the building end-life. The results showed that the use phase involved the most significant energy consumption, accounting for 75% of the total primary energy demand. The construction phase required 19% of the total energy demand, while the maintenance and end life phases accounted for 6% of the total primary energy demand [12]. A more detailed analysis of the use phase showed that the electricity consumption was dominant, followed by the use of LPG for house heating, hot water demand and cooking. A large part of the consumptions were related to the use of household appliances and other electrical equipment.

The energy needed for operation could be significantly reduced by adopting a technical solution, such as improving the thermal insulation of the building envelope or introducing efficient technology. Furthermore, the embodied energy could be reduced by suitable refurbishment, recycling and reuse of materials and components. It is necessary to study the environmental impact of buildings to avoid shifting problems from one part of the life cycle to another or from one geographical area to another.

A survey of the references in the scientific literature illustrates a substantial lack of studies specifically focused on building retrofit and refurbishment actions. The following chapters summarise the results of an energy and environmental assessment of a set of retrofit actions implemented in the framework of the EU Project "BRITA in PuBs" (Bringing Retrofit Innovation to Application in Public Buildings – no: TREN/04/FP6EN/S07.31038/503135) [21].

It was an EU-supported integrated demonstration and research project that aimed to (1) increase the market penetration of innovative and effective retrofit solutions; (2) improve energy efficiency; and (3) implement renewable energy in public buildings all over Europe.

The study aimed at drawing a balance between energy and environmental benefits and drawbacks concerning exemplary building retrofit actions, such as the introduction of insulation and windows with high thermal efficiency, installation of renewable energy plants, and efficient HVAC and lighting. A life cycle approach was applied according to the standards of the ISO 14040 series [22].

The analysis allowed the partners of the project to define and select the best energy and environmental improvements from the design to the completed building renovation.

The environmental burdens of retrofits were assessed to estimate the order of magnitude of the impact and to identify environmental "hot spots" of retrofits, i.e. materials and components with the highest environmental burdens.

3. Environmental analysis of building retrofit

3.1. Description of the case studies

A brief description of the retrofit actions implemented in six public buildings (or *case studies* in the remainder of the paper) is provided in this chapter.

(1) Partner: Brno University of Technology – Building: Old Brewery, Brno (total floor area after the intervention: 2660 m^2). The retrofit was applied to the old city "Brewery" located in the historical centre. The building served as a warehouse for many years; thus, no usable heating system existed in the building before retrofitting. The coal-fired heaters (stoves) were used for heating in the past, but these had not been in operation since the building became a warehouse. The building was naturally ventilated, but there were no openings for the air supply except for the windows. The former brewery has been transformed into a modern social and cultural centre for students and academics, which included a structural renovation of the building and an energy retrofit by installing several innovative components, such as new thermal insulation of the surfaces, high-efficiency windows, high-efficiency HVAC systems, condensing gas boilers, and photovoltaic (PV) panels.

(2) Partner: SunLab – Building: Hol Church, Gol (total floor area after the intervention: 555 m^2). The retrofit was performed on an ancient Norwegian timber church. The actions included removing rotted timber, installing rockwool insulation, introducing an innovative solar assisted heating system, and installing PV panels and energy-efficient light bulbs.

(3) Partner: Plymouth College of Further Education – Building: College, Plymouth (total floor area after the intervention: 5794 m^2). The retrofit was performed in the existing city college in Plymouth and included specific energy-saving actions. The existing building was erected using a simple cavity wall construction and single glazed windows, all of which results in very low insulation values. The existing walling is typical of its time with an outer face of imperial-sized bricks and a 50-mm dry cavity with no insulation. Existing window units are single panes in metal frames. The external facades, as is common with many buildings of its type and age, are now in a poor state of repair, and suffer particularly because of their close proximity and exposure to the South West coast line and its prevailing weather conditions. Available data on wind exposure and prevailing wind direction in addition to the outlook of the site suggested that it would be appropriate to install wind turbines. Thus, two wind turbines (with a nominal power of 6 kW each) were installed on the roof of the building, 21 m above ground level. Other modifications for heating, cooling and lighting control, solar glare control, and thermal gains reduction were designed but not yet realised.

(4) Partner: Cenergia – Building: Prøvehallen, Copenhagen (total floor area after the intervention: 2300 m^2). The site was an old industrial area that was completely reshaped and turned into a modern low energy and multifunctional cultural centre. Proevehallen had not been used for a number of years. Because of its original purpose, it had been built as a minimal construction with no insulation in the walls and simple single glass metal frame windows. No energy consumption data from before the retrofit were available for comparison to the energy-saving design. Thus, the savings had to be compared to the existing requirements in the Danish building regulations. The retrofit was essentially characterised by the installation of additional insulation of the external enclosure of the buildings, low-energy windows, and a "demand controlled" mechanical and natural ventilation system. Two PV plants were installed: an array of PV cells on the south gable wall, and an innovative photovoltaic/thermal (PV/T) solar collector cooled by a heat pump to increase the efficiency of the PVs. The produced electricity is used in the building or sold to the electricity grid.

(5) Partner: City of Stuttgart – Building: Nursing Home, Stuttgart (total floor area after the intervention: 2131 m^2). The heating system had an old measurement control system. The boiler system did not work very efficiently because of the falling insulation and the missing control system. Opening the windows was the only ventilation system; no mechanical ventilation system was installed. A cooling system in this habitation-like building in Germany is not necessary. The lighting system consists of energy-saving fluorescent tubes and bulbs in the rooms and traffic areas. It was controlled by manual on/off switches. An example is shown in Fig. 8. The lighting system did not work efficiently. The power of the installed lighting system ran up to 12.5 W/m^2 for 300 lx. The retrofit project included many integrated renovation actions, including energy retrofit of structures, wall insulation with mineral-fibre wool, substitution of old facades with high performance windows (triple glasses with a *U*-value of 1 W/(m^2 K) and thermal spacers to reduce the thermal bridges at the edges), and installation of high performance heating and ventilation systems. Furthermore, a thermal solar plant was installed to provide 32% of the domestic hot water demand. Moreover a PV system with a yearly production of 12.6 kWh/y was realised.

(6) Partner: Vilnius Gediminas Technical University (VGTU) – Building: VGTU main building, Vilnius (total floor area after the intervention: 8484 m^2). The thermal transmittance of the walls was 1.07 W/(m^2 K). After 30 years of exposure, both the sun and rainfall impacted the partitioned external sectors. Somewhere, connection junctures of three-layer panels are already partly crumbled and pervious to moisture. The juncture in damaged places of the external sectors partitioned off was sealed with warm sealing material and stopped up with a sealant. The renovation of the VGTU case study mainly involved (1) renovating old facades and the roof; (2) substituting old wall insulation with higher thermal performance materials; (3) installing high-efficiency windows with selective glasses and low thermal transmittance; (4) renovating the heating system; (5) replacing the old heating and ventilation systems with fully automated ones.

Pictures of the case studies before and after the retrofit interventions are shown in Fig. 1.

3.2. Key methodological issues and data quality

The environmental assessment of the case studies was performed by coupling field data with referenced eco-profiles of the main building products and processes applied in the project. Information about retrofit actions arose from:

- designs, including the description of construction materials, plants, energy-efficient components and technologies to exploit renewable energy sources;
- checklists and questionnaires for a data survey during the construction and implementation of the retrofits. They included also data regarding waste production and energy consumption of construction machinery;
- monitoring data, which concerned the energy consumption of buildings and the energy production energy systems.

Concerning methodological issues, retrofit actions are likely to be conceptually complex because they include other concepts, such as economic and aesthetic considerations, besides the energy and environmental aspects. The final choices depend on a variety of environmental technological and economic mechanisms.

Therefore, a preliminary list of the foreseeable consequences that are potentially important for the energy and environment, due to the retrofit actions, was prepared. Afterwards, the potential key-issues enclosed in the list were discussed with a network of experts involved in the project. No single person is an expert on all fields. Thus, a combination of experts was selected from the group of participants to complete questionnaires on numerical data and qualitative judgements.

Questionnaires were provided to the project participants to collect data regarding both the design stage and the implementation of the retrofit actions. In particular, the requested information concerned the following categories:

- building materials used for the retrofit work, with particular attention to their thermal properties;
- window typologies and characteristics;
- lighting equipment;
- innovative and traditional heating systems;
- PV and solar thermal collectors;
- ventilation systems;
- pipes and ducts;
- energy consumption of machinery utilised during retrofit work;
- waste produced during construction.

Table 1 shows the direct energy consumption in the case studies, before the retrofit actions, and the direct energy savings by renovating the building components, materials and technologies; these data were collected among the project partners by means of questionnaires.

The greatest difficulties concerned the availability of inventory data. Because a detailed analysis of each construction component

Fig. 1. Buildings before and after the retrofit interventions.

Table 1
Data collected by questionnaires from the project partners on the energy consumption before the retrofit actions.

Case study	Energy use before retrofit [GJ/year]	Retrofit actions	Measured/estimated energy saving after retrofit [GJ/year]
Brewery – Brno			
Space heating	2376	Insulation of roofs and facades	202
		Low-e windows	269
		Condensing boilers	375
		Control of heating	77
		Waste heat recovery	248
		CO_2 controlled hybrid ventilation	72
Total heating energy saving			1243
Electricity	588	Photovoltaic modules	119
		Heat pump	14
Total electricity saving			133
Hol Church – Gol			
Space heating	440	Insulation flat part of roof and under floor	198
		Solar thermal system	7
Total heating energy saving			205
Electricity	74	Solar PV	1
		Efficient lighting	35
Total electricity saving			36
College – Plymouth			
Space heating	4320	n.d.	
Electricity	2336	Wind turbines	41.4
Provehallen – Copenhagen			
Space heating	No data	High efficient ventilation	425
		Improved insulation facade and roof	54
		Low-e windows	72
		Heating energy savings	83
		Combined PV and Thermal heating system	59
Total heating energy saving			693
Electricity	No data	High efficient fans in the ventilation	112
		Electrical output of PV/T cells	22
		PV-cells	58
Total electricity saving			192
Nursery home – Stuttgart			
Space heating	2446	High efficient windows	153
		Insulation of the opaque elements	603
		Ventilation	297
		Heating system	345
		Solar heating system	84
Total heating energy saving			1482
Electricity	472	Heating system	284
		CHP	
		Efficient lighting	77
		Daylighting transfer	23
		PV-system	49
Total electricity saving			433
Vilnius			
Space heating	5437	High-efficient windows	794
		Insulation of roofs and facades	852
Total heating energy saving			1546
Electricity	1101		

was beyond the goals of the project, national and international environmental databases were investigated to select representative eco-profiles of products and systems [23–27]. Data were deduced from references and adapted to the specific retrofit context when not available.

The experts defined a Data Quality Index (*DQI*), a subjective index that provides a qualitative judgement of the quality of data through a set of judgements according to the following indicators:

1. Age of data.
2. Geographical relevance of data, which is the degree of accordance between the production features of the artefacts in the examined area and those in the geographical area covered by secondary data.
3. Technological relevance of data, which expresses the representativeness of the eco-profile used for the technology under study.

For each of the above indicators, qualitative judgements were assigned, as shown in Table 2. The table represents a matrix, which allows every qualitative indicator to be judged by means of a score between 1 and 3. "1" represents the best score, while "3" represents the worst. The starting point of the applied method was derived from [28]. The final *DQI* from a subjective combination of these indicators gave a result of *low*, *medium* or *high*.

The following were considered to determine the quality and available data.

- The impact of building retrofit materials referred to average European data, as presented in the international LCA databases, has a *high DQI*.
- Eco-profiles of electricity referred to the average national energy mix of each different country have a *high DQI*.

Table 2
Indicators for the *DQI* definition derived from [27].

Indicator score	1	2	3
Age of data	More than 10 years of difference to year of study or unknown age	Less than 10 years of difference to year of study	Less than 3 years of difference to year of study
Geographical relevance	Data from unknown area or from area with very different production conditions	Data from area with similar production conditions	Data from the area under study
Technological relevance	Unknown technology or data on related processes or material, but from different technology	Data from processes and materials under study, but different technology	Data from processes and materials under study.

- The impact of glazing components, wall panels and pipes were assessed by similar construction typologies that were included in the international LCA databases. The data were modified proportionally to their geometric dimensions. Therefore, the *DQI* is *medium*.
- The impact of waste management relative to that used in average European contexts has a *medium DQI*.
- The impact of solar plants (PV and thermal) was assessed based on similar results recorded in the environmental databases and were modified proportional to their surface or installed power. The *DQI* is *low*.
- The impact of HVAC systems was deduced from eco-profiles of similar plants, modified proportionally to the installed power. Also, in this case *DQI* is *low*.

A key issue is also represented by the expected life-time of each retrofit component/technology/equipment (Table 3). The main assumptions were deduced from the technical reports from suppliers.

3.3. Energy and environmental indices

The results of the environmental analysis are presented according to the data format of the Environmental Product Declaration (EPD) scheme [27]. Therefore, GER (Gross Energy Requirement), GWP (Global Warming Potential), AP (Acidification Potential), EP (Eutrophication Potential), ODP (Ozone Depletion Potential), and POCP (Photochemical Ozone Creation Potential) have been calculated.

Payback indices were added to the EPD set for a deeper description of the energy performance of the retrofit actions and to compare different alternatives [29,30]:

- The *Energy Payback Time* (E_{PT}) of a building retrofit action is the time needed to save as much energy (valued as primary) as that consumed during all the life cycle phases of each retrofit component/material/technology:

$$E_{PT} = \frac{GER}{E_{s,y}}$$

where GER is calculated with regard to the life cycle of the retrofit action (GJ); $E_{s,y}$ is the yearly saving of primary energy due to the retrofit action ($GJ_{primary}$/year).

The yearly direct saving of electricity and heat was estimated by the project partners at the design stage of the retrofit actions or measured after the retrofit was completed (Table 1). Such data were converted into primary energy based on the energy mix for the production of electricity and other energy sources for each considered country. Energy mixes of countries were derived from international databases [23,24].

- The *Emission Payback Time* is the time during which the avoided emissions by the application of the retrofit actions are equal to those released during the life-cycle phases of each component. As a result of a clear agreement within the scientific board of the BRITA Project, the partners decided to calculate the Em_{PT} with regard to the GWP index to express the environmental pollution [31–33]. Then it was defined as:

$$Em_{PT,GWP} = \frac{GWP}{GWP_{s,y}}$$

where GWP is calculated with regard to the life-cycle of each retrofit action (kg $CO_{2\text{-eq}}$); $GWP_{s,y}$ is the GWP avoided yearly after the retrofit (kg $CO_{2\text{-eq}}$/year) It also represents the GWP, which arises from the building if no retrofit action performed. Then, it depends on the typology and efficiency of the used plants. It is based on the previously assessed $E_{s,y}$ and on the reference emission factor of each electricity mix and national gas-fired heating plants [14].

- The *Energy Return Ratio* (E_R) represents how many times energy-saving exceeds global energy consumption:

$$E_R = \frac{E_S}{GER}$$

where E_S is the total saving of primary energy during the lifetime of each retrofit action (GJ). E_R includes GER and the energy saving during the building operation.

Table 3
Assumed life span for each component/technology/equipment.

Component	Lifetime (years)
Lighting equipments	3
Small wind turbines	15
HVAC systems	15
Solar thermal plants	15
PV plants	20
Building components	35

3.4. Results

3.4.1. Case study: Brno

The retrofit of the Brewery building (Brno) included the following actions:

- renovating the building envelope with new thermal insulation and high-efficiency windows to reduce the thermal losses and the lighting need;
- installation of PV panels and of high-efficiency technology for heating and ventilation.

Fig. 2 compares GER to total energy saving, while Fig. 3 shows the contribution to GER of each retrofit phase. The construction phase required the use of electricity and diesel oil to operate the machinery. The disposal scenario included the transportation of wastes coming from the building site and their disposal to local landfills. It is observed that the highest GER is due to the PV plants, while insulation and window replacement represent 4% and 3% of GER, respectively. The construction phase represents 19% of GER, while the contribution due to wastes disposal is 4% of GER.

The retrofit of the building envelope provides yearly primary energy savings of 586 GJ/year. In particular, the building insulation

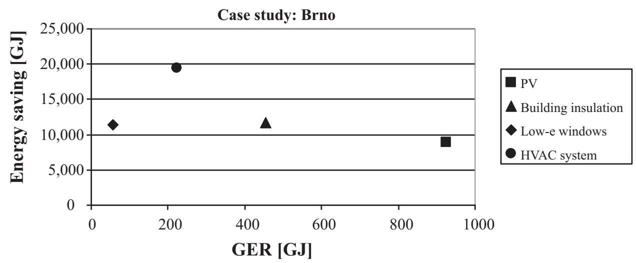

Fig. 2. Comparison among GER and total energy saving in Brno case study (Brewery).

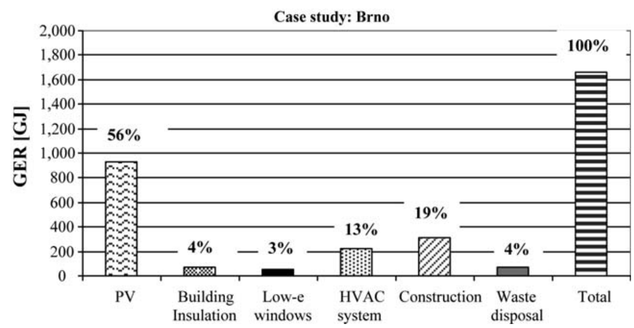

Fig. 3. Contribution to GER of each retrofit phase in Brno case study (Brewery).

was improved with mineral wool boards of 100 mm for the facade and the roof, and with 60 mm polystyrene boards for the ground floor. Such actions involved a primary energy saving of 126 MJ/(m^2 year), while the introduction of low-e windows saves 123 MJ/(m^2 year).

As indicated in Table 1, installation of the PV panels provided a yearly electricity saving of 119 GJ/year. The related primary energy saving is 443 GJ/year, that is 156.5 MJ/(m^2 year).

The high-efficiency HVAC system involved a yearly electricity saving of 14 GJ/year and a yearly heat saving of 772 GJ/year. The related primary energy-saving was 1292 GJ/year, which is 486 MJ/(m^2 year) for a total floor area of 2660 m^2.

3.4.2. Case study: Gol

The retrofit of Hol Church (Gol) included the following actions:

- renovation of the building roof and under floor, by means of new thermal insulation and high-efficiency windows to reduce the thermal losses and the lighting need;
- installation of PV panels and of a solar thermal system;
- introduction of efficient lighting.

Fig. 4 compares GER to total energy saving, and Fig. 5 shows a contribution to GER of each retrofit action. It is observed that the highest GER is due to the building insulation, while the construction phase represents 10% of GER. The lighting system is negligible. Building is also the retrofit action that involves the highest total energy-saving (8612 GJ).

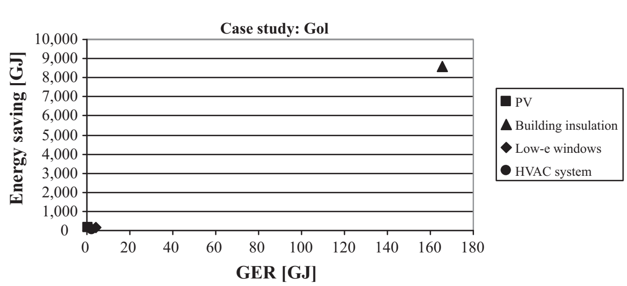

Fig. 4. Comparison among GER and total energy saving in Gol case study (Hol Church).

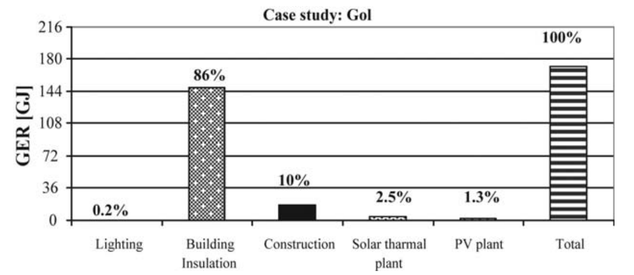

Fig. 5. Contribution to GER of each retrofit phase in Gol case study (Hol Church).

The retrofit of the building roof and floor provides a yearly saving of primary energy of 246 GJ/year, that is 443 MJ/(m^2 year), for a total floor area of 555 m^2.

Installation of the PV panels provided a yearly saving of 1 GJ/year of electricity. The related primary energy-saving is 1.5 GJ/year, which is about 3 MJ/(m^2 year). The solar thermal system saves 7.2 GJ/year. The related primary energy-saving is about 9 GJ/year, that is 16.2 MJ/(m^2 year). Concerning the efficient lighting, the yearly saved electricity is 35 GJ/year and the related primary energy-saving is 50 GJ/year. The primary energy-saving per unit of floor area is 90 MJ/(m^2 year).

3.4.3. Case study: Plymouth

The retrofit of Plymouth College included the installation of two 6-kW wind turbines to reduce the electricity demand of the site.

The yearly saving of electricity provided by the retrofit action is 41.4 GJ/year with a primary energy saving of 143 GJ/year. The total floor area is 5794 m^2, and the specific primary energy saving is 24.6 MJ/(m^2 year).

3.4.4. Case study: Provehallen

The retrofit of Provehallen (Copenhagen) included the following actions:

- the reduction of the envelope thermal transmittance by means of the facade and roof insulation, and by means of the installation of high-efficiency windows;
- the installation of a PV plant and a PV/T solar collector, which is cooled by a heat pump to increase the efficiency of the PVs.
- the installation of a high-efficiency HVAC system.

Fig. 6 compares GER to total energy saving, while Fig. 7 shows the contribution to GER of each retrofit phase. It can be noted that the building insulation and the low-e windows have the highest contribution to GER and the lowest energy saving, compared to the other retrofit actions. The efficient HVAC system provides the

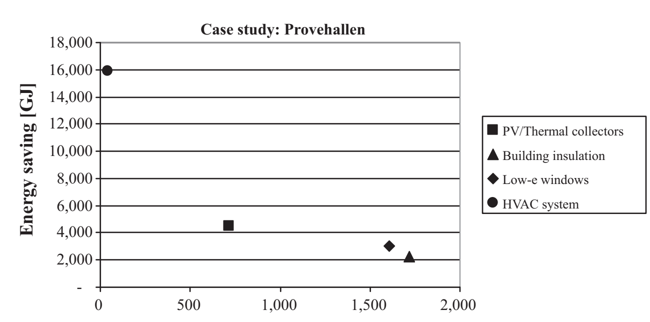

Fig. 6. Comparison among GER and total energy saving in Provehallen case study.

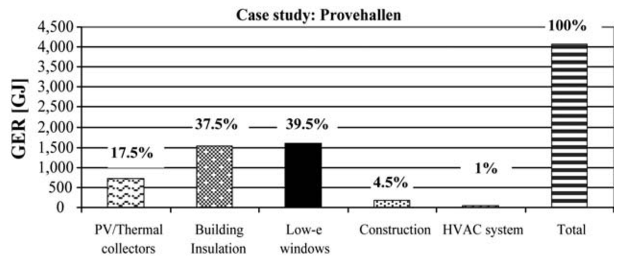

Fig. 7. Contribution to GER of each retrofit phase in Provehallen case study.

lowest GER (1%) and the highest energy saving. The construction phase represents 4.5% of GER.

Based on the results of the energy and environmental analyses of the case study, the retrofit of the building envelope provides a yearly saving of primary energy of 151 GJ/year and a direct heat saving of 126 GJ/year. In particular, the insulation of the building was made with mineral wool boards, which lead to energy savings of 65 GJ/(year), while the introduction of low-e windows involves energy-saving of 86 GJ/(year). With a total floor area of 2300 m^2, the primary energy saving are 28 MJ/(m^2 year) and 37.5 MJ/(m^2 year), respectively.

Installation of the PV/T solar collector globally saved 302 GJ/year, that is 131 MJ/(m^2 year). Concerning the high-efficiency HVAC system, the yearly primary saved energy is 2113 GJ/year, that is 919 MJ/(m^2 year).

3.4.5. Case study: Stuttgart

Renovation of the Nursery Home (Stuttgart) involved the following actions:

- insulation of the envelope opaque elements and high-efficiency windows to reduce the thermal losses;
- installation of a solar heating system and a PV plant;
- installation of high-efficiency technology for heating and ventilation (HVAC).

Fig. 8 compares GER to total energy saving, and Fig. 9 shows the contribution of each retrofit action to GER.

The yearly heat saving due to the retrofit of the building envelope was 756 GJ/year, and the related primary energy saving was 1021 GJ/year. In particular, the improvement of the building insulation saved 352 MJ/(m^2 year), while the introduction of low-e windows involves an energy-saving of 127 MJ/(m^2 year). The total floor area is 2131 m^2.

The installation of the PV panels saved 49 GJ/year in electricity, and the related primary energy saving is 81 MJ/(m^2 year). The solar thermal plant provides heat savings of 84 GJ/year and a primary energy saving of 866 MJ/(m^2 year). The high-efficiency HVAC system saved 284 GJ/year and a provided yearly heat savings of 642 GJ/year. The saved primary energy was 841 MJ/(m^2 year).

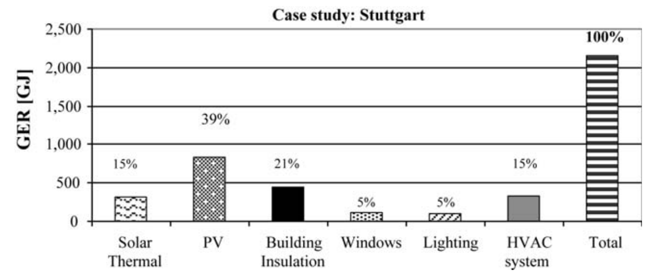

Fig. 9. Contribution to GER of each retrofit phase in Stuttgart case study (Nursing Home).

With regard to lighting, the installation of an efficient lighting system together with the improvement of the daylight transfer saved 100 GJ/year in electricity. The saving of primary energy is 349 GJ/year, that is 163.6 MJ/(m^2 year).

3.4.6. Case study: Vilnius

The retrofit of the VGTU main building (Vilnius) included the following actions:

- replacement of old thermal insulation of the walls and installation of high thermal performance materials in the building envelope;
- replacement of the old windows with high-efficiency ones characterised by low emissivity glasses and low thermal transmittance;
- renovation of the roof with the introduction of a waterproof layer.

The assessed energy saving was 794 GJ/year from the high-efficient windows, and 852 GJ/year due to insulation and renovation of roofs and facades. These values were converted into primary energy values by taking into account the efficiency of the Lithuanian energy mix. In detail, the primary energy saving due to the high-efficient windows is 116 MJ/(m^2 year), while the insulation of the building envelope provides a primary energy saving of 125 MJ/(m^2 year). The total floor area of the studied building is 8484 m^2.

Fig. 10 compares GER to total energy saving and Fig. 11 shows the contribution to GER of each retrofit action. It is observed that the manufacturing of materials gives the highest impacts. In particular, insulation and window replacement are each responsible for about half of the GER. The construction phase represents about 5% of GER, while the contribution from wastes disposal is almost negligible. The construction phase required the use of electricity and diesel oil to operate the building machineries. The disposal scenario included the transportation of wastes coming from the building site and their disposal to local landfills.

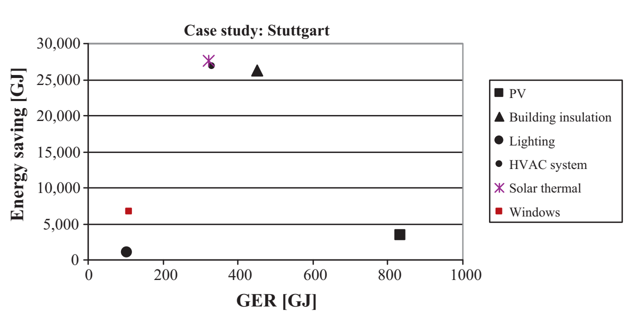

Fig. 8. Comparison among GER and total energy saving in Stuttgart case study (Nursing Home).

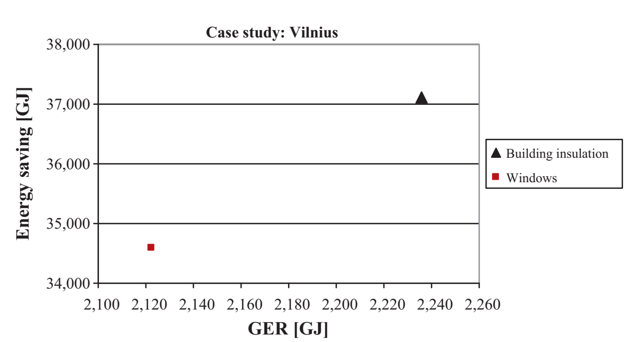

Fig. 10. Comparison among GER and total energy saving in Vilnius case study (VGTU main building).

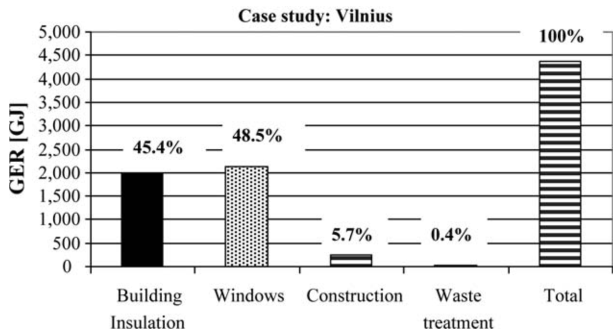

Fig. 11. Contribution to GER of each retrofit phase in Vilnius case study (VGTU main building).

The specific GER and GWP of the two window typologies (PVC and the aluminium frames) were estimated from references [25–27] and reported in Table 4. The results indicate that aluminium causes an impact 3–4 times larger than that the PVC, which is derived from the assumption that primary aluminium was employed in the window manufacture.

3.5. Discussion of the results

For each case study, the retrofit actions involve about 50% of energy saving for heating, except for Plymouth, where no intervention for heat saving is performed, and for Vilnius, where the energy saving is about the 30%. Concerning electricity, the highest saving is reached in the Stuttgart case study (90%). The electricity saving gained at Plymouth College with the wind turbines is just 2% of the yearly consumption; thus, this action has unsatisfactory results (see Table 1).

Table 5 shows the outcomes of the environmental indices for each case study. It is worth noting that the results are not numerically comparable because of the different complexity and scale of interventions. Concerning the GER and GWP, two sets of building retrofits with different and extended interventions can be identified: (1) Stuttgart, Vilnius, Proevehallen and Brno case studies, which involve high values of GER and GWP; (2) Gol and Plymouth case studies, with smaller and more focused actions that involve lower GWP and GER values. The other environmental indices, such as AP, EP, and POCP, follow a similar trend to the GER and GWP.

Table 4
Comparison of two window typologies.

	1 m^2 of aluminium window	1 m^2 of PVC window
GER [GJ]	3.6	1.2
GWP [kg $CO_{2\text{-eq}}$]	204.7	48.1

Table 6 shows the energy and GWP payback times calculated for each action. The total energy investment and environmental impact due to the actions are fully repaid by the obtained benefits in a short period. Therefore the expected life-time of the retrofits saves energy and reduces $CO_{2\text{-eq}}$ emissions. It is evident that the highest payback times result for the PV plants for each case study, except for Provehallen, where the renovation of the building envelope involves high values for E_{PT} and $Em_{PT,GWP}$. Such action provides the highest GER and the highest GWP with the lowest energy saving and the lowest environmental benefit (avoided GWP).

Fig. 12 illustrates a plot of GER values vs. the primary energy savings for each case-study. This diagram allows the different retrofits to be compared and to assess the best effective actions. Actions with greater energy savings are in the upper-left of the diagram with the lowest initial energy investment. Fig. 13 shows a comparison of the Energy Return Ratio. All implemented actions are characterised by relevant energy benefits. Energy saving overcomes the total energy consumption a minimum of 6 times (Proevehallen case study) to a maximum of 52 times (Gol case study).

Table 5
Environmental indices for each case study.

Building	Index	Benefits	Impacts	Net benefits
Brewery – Brno	GER [GJ]	51,382	1657	49,725
	GWP [10^3 kg $CO_{2\text{-eq}}$]	3087	82	3005
	ODP [kg $CFC_{11\text{-eq}}$]	0.28	0.03	0.25
	AP [kg $SO_{2\text{-eq}}$]	4847	598	4249
	EP [kg $PO_4{}^{3-}{}_{eq}$]	394	59	335
Hol Church – Gol	GER [GJ]	8927	172	8755
	GWP [10^3 kg $CO_{2\text{-eq}}$]	499.5	10.5	489
	ODP [kg $CFC_{11\text{-eq}}$]	0.06	0.00	0.06
	AP [kg $SO_{2\text{-eq}}$]	377	60	317
	EP [kg $PO_4{}^{3-}{}_{eq}$]	41	7.6	33.4
College – Plymouth	GER [GJ]	2142	97	2045
	GWP [10^3 kg $CO_{2\text{-eq}}$]	117	7	110
	ODP [kg $CFC_{11\text{-eq}}$]	0.003	0.000	0.003
	AP [kg $SO_{2\text{-eq}}$]	415	32	383
	EP [kg $PO_4{}^{3-}{}_{eq}$]	30	2.4	27.6
Prøvehallen – Copenhagen	GER [GJ]	25,748	4078	21,670
	GWP [10^3 kg $CO_{2\text{-eq}}$]	2697	216	2481
	ODP [kg $CFC_{11\text{-eq}}$]	0.15	0.05	0.10
	AP [kg $SO_{2\text{-eq}}$]	2494	987	1507
	EP [kg $PO_4{}^{3-}{}_{eq}$]	205	118	87
Nursing Home – Stuttgart	GER [GJ]	91,983	2151	89,833
	GWP [10^3 kg $CO_{2\text{-eq}}$]	5230	115	5115
	ODP [kg $CFC_{11\text{-eq}}$]	0.37	0.04	0.33
	AP [kg $SO_{2\text{-eq}}$]	3852	753	3099
	EP [kg $PO_4{}^{3-}{}_{eq}$]	401	56	345
Vilnius	GER [GJ]	71,717	4358	67,359
	GWP [10^3 kg $CO_{2\text{-eq}}$]	4077	218	3859
	ODP [kg $CFC_{11\text{-eq}}$]	0.40	0.16	0.24
	AP [kg $SO_{2\text{-eq}}$]	3206.0	1253	1953
	EP [kg $PO_4{}^{3-}{}_{eq}$]	334	111	223

Table 6
Energy and GWP payback times indices for each retrofit action.

Building	GER [GJ]	Primary energy saving [GJ]	E_{PT} [year]	GWP [10^3 kg $CO_{2\text{-eq}}$]	Avoided GWP [10^3 kg $CO_{2\text{-eq}}$]	$Em_{PT,GWP}$ [year]
Brno						
PV	926	8859	2.1	42	608	1.4
Building insulation	454	11724	1.4	26	666	1.5
Low-e windows	55	11414	0.2	2	680	0.1
HVAC system	222	19385	0.2	11	1133	0.2
Total	1657	51,382	0.7	82	3087	0.6
Gol						
Lighting	0.3	150	0.01	0.02	2	0.03
Insulation	165.5	8612	0.7	10.15	490	0.73
Solar thermal plant	4.1	134	0.5	0.22	7.5	0.44
PV plant	2.1	31	1.5	0.10	0	6.1
Total	172	8927	0.6	10.49	499.5	0.7
Plymouth						
Wind turbines	97	2142	0.68	7	117	0.9
Prøvehallen						
PV/thermal plant	716	4533	2.4	37	390	1.9
Building insulation	1716	2262	26.5	117	129	31.9
Low-e windows	1604	3016	18.6	58	172	11.8
HVAC system	42	15,937	0.04	3	2007	0.03
Total	4078	25,748	2.7	216	2697	1.3
Stuttgart						
Solar thermal plants	323	27,680	0.2	18.5	1574	0.2
PV	833	3449	4.8	37.7	196	3.8
Building insulation	452	26,255	0.6	32.7	1493	0.8
Windows	110	6681	0.6	0.1	380	0.01
Lighting	104	1046	0.3	6.7	59	0.3
HVAC system	330	26,871	0.2	19.5	1528	0.2
Total	2151	91,983	0.4	115.1	5230	0.4
Vilnius						
Insulation	2236	37,120	0.5	85.0	2110	1.4
Windows	2122	34,597	0.5	133	1967	2.4
Total	4358	71,717	2.1	218	4077	1.9

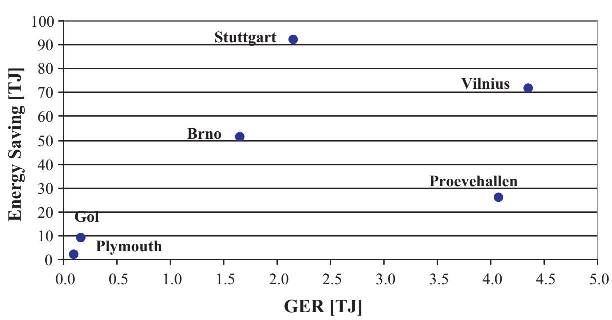

Fig. 12. Comparison among GER and Energy saving.

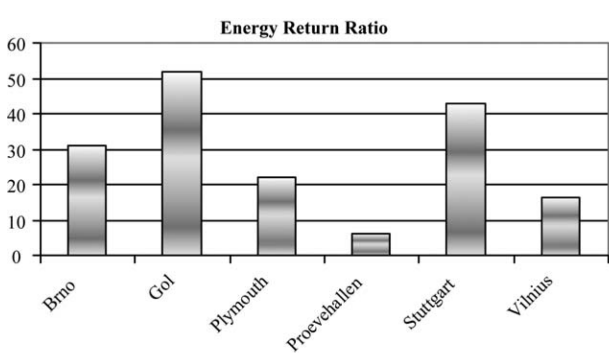

Fig. 13. Energy Return Ratio Index in each case study.

4. Conclusions

The environment-oriented design of buildings is a complex task. Energy and environmental performances of buildings strictly depend on many factors related to the choice of construction materials, HVAC plants and equipment, design, installation and use. By definition, an eco-building closely interacts with its environment. In such a building natural phenomena, such as natural ventilation, day lighting, passive cooling and heating, and renewable energy sources, are integrated in a thermal insulated envelope framework with energy efficient systems.

Then interactions between building and climate, plants, and users have to be taken into account. This aspect is evident in new buildings design process, but it is even more important in the design phase of an existing building renovation, during which energy saving actions are developed.

Several studies on the design phase of buildings have been carried out, but few analyses have developed the environmental implications of retrofit and refurbishment actions.

The presented research analyses suggest several case-study actions to retrofit public buildings all over Europe. The results are part of the research project "*BRITA in PuBs – Bringing Retrofit Innovation to Application in Public Buildings*", funded by the European Commission within the EU 6th Framework Programme. The energy and environmental analyses were developed to support the project participants in the assessment and selection of the most effective and low-impact solutions. The main goal was to improve building energy and environmental performances following a life-cycle approach. The use of such an approach was very successful and potentially transferable to other contexts of building retrofit study.

The analysis was based on design assessment, on-field measurements of energy and material consumptions, and processing reference data about component eco-profiles. The aim of the research was to determine the balance of energy and environmental benefits and drawbacks for retrofit actions. The analysis was based on information provided by the partners of the project. The survey has been carried with specific questionnaires distributed to each partner. Questionnaires included both information at the design stage and information collected during the retrofit

exploitation. The goal of the questionnaire was to guide partners into data collection and to harmonise the analysis outcomes.

Looking at the assessment outcomes, the most significant benefits (energy saving and avoided GWP) are mainly related to improvement in the envelope thermal insulation (high-efficiency windows, and thermal insulating boards). Substitution of insulation, lighting and glazing components provided particularly efficient solutions. In all the case studies, renovation of HVAC plants and lighting systems provides significant energy benefits. Both for solar and wind plants, a generally overestimated energy production at the design stage was observed with respect to that monitored. That involved lower energy savings and higher payback indices than those predicted.

Acknowledgment

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